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Room-Temperature Operation of VCSEL-Pumped Photonic Crystal Lasers

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***Abstract*—Room-temperature operation of two-dimensional photonic crystal lasers optically pumped by a vertical-cavity surface-emitting laser emitting at 860 nm is reported. The photonic crystal membrane is surrounded by air on both sides and consists of four compressively strained quantum wells as the active region. The incident threshold pump power of an approximately 2.6-μm-diameter hexagonal defect cavity laser operating at 1.6 μm is 2.4 mW.**

***Index Terms*—InGaAsP–InP, microcavities, photonic crystals, semiconductor lasers.**

I. Introduction

EMISSION of optical radiation can be modified by placing a gain medium inside a cavity [1]. In 1987, [2] and [3] proposed that photonic bandgap cavities could be used to accomplish this modification. As a result, ultralow threshold photonic crystal defect lasers that are attractive components in high-speed optical interconnect applications can be expected. Due to the simplicity of fabrication and numerical simulation, two-dimensional (2-D) photonic crystals have drawn much more attention compared to their three-dimensional counterparts. The flexibility in defining the geometry of the monolithically integrated device makes photonic crystals promising candidates for application to waveguides, light sources, optical filters, and switches. Recently, photonic crystal defect lasers with different designs and cavity sizes have been realized [4]–[7]. Furthermore, a 2-D wavelength-division-multiplexed photonic crystal defect laser array formed by varying the lattice parameters of individual elements has also been demonstrated showing the ability to fine tune the emission wavelength [8]. In this publication, we present results on photonic crystal lasers optically pumped by a vertical-cavity surface-emitting laser (VCSEL). This demonstration validates the low threshold potential of these laser elements and suggests a technique for their excitation.

II. Design and Fabrication

Optical resonant microcavities are formed here by using 2-D photonic crystals for in-plane localization and a thin dielectric slab waveguide for vertical confinement. The 2-D photonic crystal is a triangular lattice consisting of air holes and is formed on a suspended dielectric membrane. The defect cavity is formed by removing 19 holes from the lattice. This cavity is five lattice constants across which corresponds to a distance of approximately 2.6 μm across the hexagon. Triangular lattice photonic crystals were used to ensure a complete bandgap for a wide range of TE mode frequencies. The laser is fabricated from the InGaAsP material system to achieve laser operation near 1.55 μm and to take advantage of its relatively low nonradiative surface recombination rate [9]. Metal–organic chemical vapor deposition (MOCVD) was used to grow four 1.2% compressively strained InGaAsP quantum wells (QW) (10-nm QWs separated by 23-nm barriers) on an InP substrate with a total slab thickness of 224 nm. Compressively strained QWs were chosen so the emission of TE-polarized radiation is strongly preferred [9]. A scanning electron micrograph of a typical laser structure is shown in Fig. 1. The lattice constant is 550 nm and the radius of holes is 215 nm.

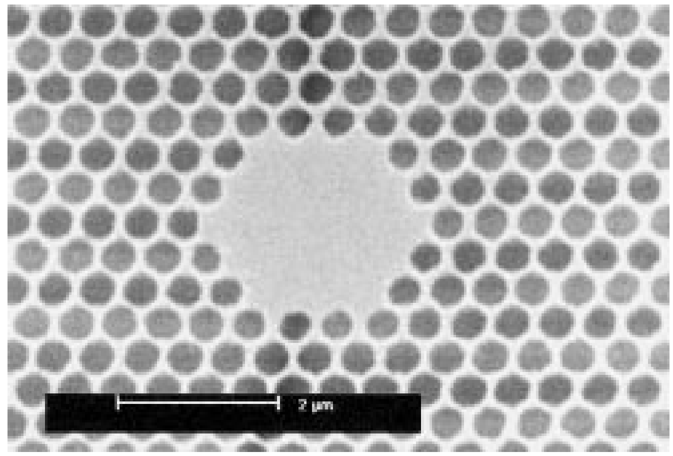

Fig. 1. Top view of a fabricated 2-D photonic crystal defect cavity. The lattice constant is 550 nm and the radius of the holes is 215 nm.

The fabrication procedure of the defect laser is as follows. First, electron-beam lithography is used to define the photonic crystal structure in 2% polymethylmethacrylate (PMMA). The pattern is then transferred into the surface mask layers using an Ar^+ ion beam etch to pattern a Cr–Au layer, and a CF_4 reactive ion etch to pattern a SiN_x layer. Electron cyclotron resonance (ECR) is used to etch holes through the active QW region and into the InP substrate. A final $HCl : H_2O = 4 : 1$ wet chemical etch is used to selectively etch away the InP, undercut the slab waveguide, and free the membrane in order to achieve the best vertical confinement. Fig. 2 shows an oblique view of a cross section of the patterned structure that is suspended across a void

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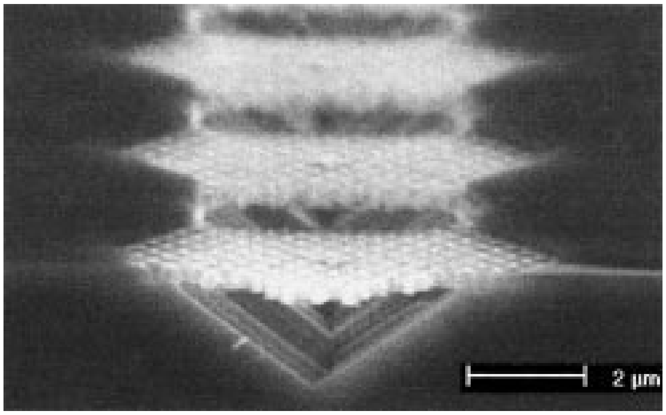

Fig. 2. Oblique cross-section view of a suspended membrane structure. The thickness of the slab waveguide is 224 nm.

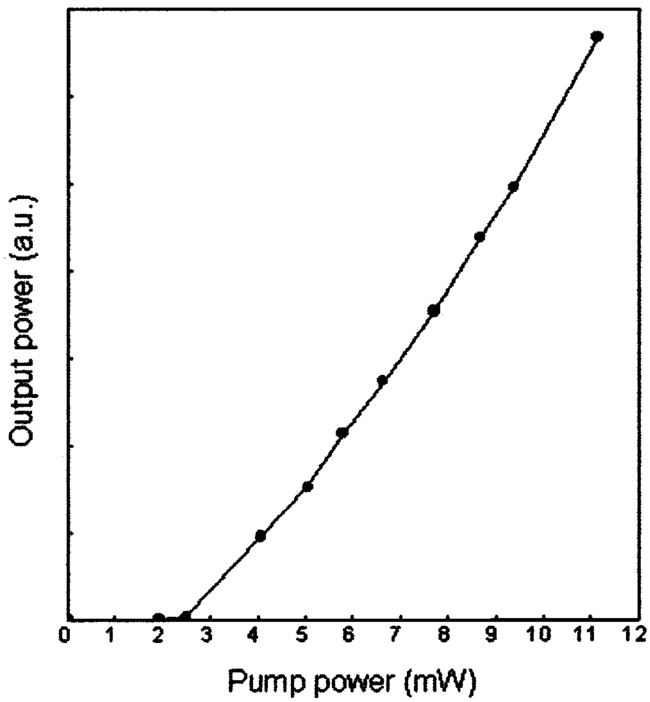

Fig. 3. L–L curve showing the power at the lasing wavelength versus the incident VCSEL pump power. The threshold pump power is 2.4 mW.

etched in the InP substrate. A more detailed description of fabrication of the V-shape undercut using HCl wet chemical etching of InP can be found in [10].

III. Measurements and Results

The sample was mounted on an X–Y–Z stage and the membrane defect cavity was optically pumped at normal incidence at a repetition rate of 0.5 to 1 MHz with up to 5% duty cycle at room temperature. An 860-nm top-emitting VCSEL was used as the pump source in this measurement. A long working distance 100× objective lens was used to focus the pump beam to a spot size of approximately 4.5 μm.

A plot of the collected output power versus the input pump power (L–L curve) for a typical defect cavity is shown in

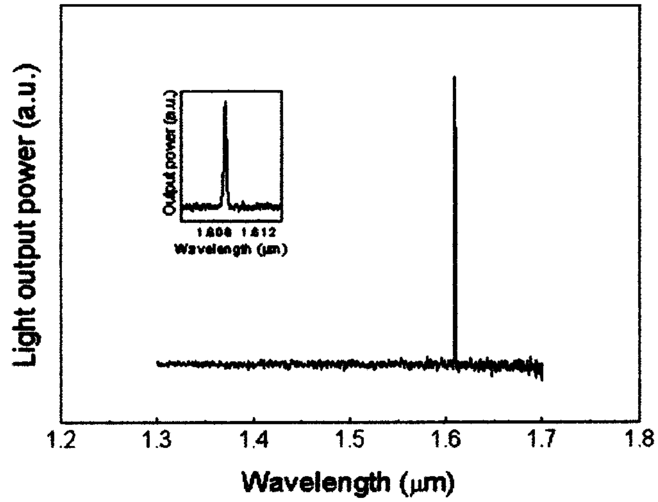

Fig. 4. Spectrum of the defect laser above threshold. The sample is optically pumped by a VCSEL with 20-ns pulses (1% duty cycle) at room temperature.

Fig. 3. The lasing spectrum is shown in Fig. 4. Room-temperature lasing with duty cycles up to 5% is observed. The laser primarily operates in a single mode, although two side modes can be observed by adjusting the pump spot size and position. The lasing wavelength is 1609 nm and the measured linewidth is limited by the resolution of our optical spectrum analyzer (0.15 nm). From the L–L curve, a threshold pump power of 2.4 mW is obtained. This value is four times smaller than previous photonic crystal lasers with similar size resonant cavities [6]. We were unable to experimentally determine the Q of the cavity. The device is lasing as soon as we can resolve peaks in the optical spectrum, so we were not able to obtain a spectrum near the optical pumping level corresponding to transparency in the InGaAsP QWs.

The defect laser reported here operates under longer pulse lengths and larger duty cycles than other similar air suspended structures. The laser operated for pulses as long as 200 ns. Due to thermal heating of the membrane we observed red shift of lasing wavelength of 1 nm when pulsewidth increased from 10 ns to 20 ns. For pulsewidths longer than 200 ns, we observed resonances in the spectrum but the structures no longer lase. We attribute this to a reduction in peak gain due to heating in the membrane. Calculations and photoluminescence experiments on unpatterned material suggest that the membrane may be as much as 100 °C hotter than the substrate under optical pumping conditions. This suggests that a demonstration of continuous-wave (CW) operation is unlikely in suspended membranes. Continuous-wave operation will likely require the integration of the photonic crystal membrane with a low index thermally conductive substrate [7].

IV. Conclusion

In conclusion, we demonstrated pulsed room temperature operation at 1609 nm of 2-D photonic crystal defect lasers optically pumped by a top-emitting VCSEL. The threshold pump power for this laser structure is smaller compared to other similar structures.

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